BIOSYSTEMS ENGINEERING 175 (2018) 27–35

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

A compact microwave device for monitoring insect activity in grain samples☆

Alex Reimer [a,*], Kelsey Wiebe [a], Jinwei Rao [a], Bimu Yao [a,b], Yongsheng Gui [a], Fuji Jian [c], Paul Fields [d], Digvir S. Jayas [c], Can-Ming Hu [a]

[a] Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada
[b] State Key Laboratory of Infrared Physics, Chinese Academy of Sciences, Shanghai, 200083, People's Republic of China
[c] Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada
[d] Morden Research and Development Centre, Agriculture and Agri-Food Canada, Winnipeg, Manitoba, R3T 2N2, Canada

ARTICLE INFO

Article history:
Received 21 October 2017
Received in revised form
11 July 2018
Accepted 26 August 2018

Keywords:
Microwave
Insect
Detector
Resonator
Grain storage

We designed and fabricated a novel microwave device capable of detecting a single insect in grain samples. A test set-up was constructed by combining a planar active microwave resonator, a Peltier cell, and an insect cage. With the integration of a regenerative element, the active resonator had a quality factor as high as 21,600 even when placed in grain, an electrically lossy medium. The high sensitivity of the device allowed the characterisation of the activity of single adult insects *Tribolium castaneum* or *Cryptolestes ferrugineus* at different temperatures, as well as the reliable detection of single adult insects in grain samples. Our approach demonstrated the non-contact sensing technique that could assist in decision making for integrated pest management programs to monitor insects in stored grain.

1. Introduction

Global climate change and increasing human populations demand a greater and more stable food supply. Stored-product insects infest stored grain around the world (Hagstrum, Phillips, & Cuperus, 2012). They reduce the quality and quantity of grain, and in several countries there is zero tolerance for insects in stored grain (Hagstrum & Subramanyam, 2006). These insect pests are small, difficult to detect and can quickly cause damage if undetected and not controlled. The current methods (Hagstrum & Subramanyam, 2006) of detecting stored-product insects include manually or mechanically retrieving samples and manually investigating for insects by sieving the sample (Jian, Doak, Jayas, Fields, & White, 2016), using a Berlese funnel to force internal insects

☆ This document is a collaborative effort.
* *Corresponding author.*
E-mail address: alexjreimer@gmail.com (A. Reimer).
https://doi.org/10.1016/j.biosystemseng.2018.08.010
1537-5110/

out of wheat kernels (Hagstrum & Subramanyam, 2006), or placing traps inside stored grain bulks (Jian, Jayas, & White, 2014a). In laboratory settings, more sophisticated techniques such as acoustical methods (Gutiérrez, Ruiz, Moltó, Tapia, & Téllez, 2010), near infra-red (NIR) spectroscopy (Singh, Jayas, Paliwal, & White, 2009), electrical conductance (Brabec, Pearson, Flinn, & Katzke, 2010; Pearson & Brabec, 2007), and soft x-ray imaging (Karunakaran, Jayas, & White, 2003) have been used to detect insects in grain samples and inside individual kernels.

Researchers have also turned to microwaves as a tool for insect detection in grain products. Microwaves are especially useful because of their ability to penetrate common, non-conducting materials. Early uses involve radar techniques to detect insects. Microwave radar has shown to be an invaluable tool for studying airborne insect migration (Drake & Reynolds, 2012), and a radar device that can detect termites in walls is commercially available (Termatrac, 2017) and its application to stored product pest detection has been studied (Mankin, 2004). Furthermore, Jian, Jayas, White, Fields, and Howe (2014b) developed a technique using microwave heating combined with sieving to extract insects from grain more rapidly than the Berlese funnel method.

In addition to radar technology, microwaves have been used in passive planar cavities for the measurement of materials (Abduljabar, Porch, & Barrow, 2014; Boybay & Ramahi, 2012) and in biotechnology in applications such as the detection of single cell movement (Ferrier, Romanuik, Thomson, Bridges, & Freeman, 2009) and the assessment of yeast cell viability (Yang et al., 2010). These devices benefit from low power demand, compact size, on-chip integration, and the ability to perform non-contact sensing. Here, microwave cavities do not rely on the emission of microwave radiation but instead detect the changes in the resonant properties of the cavity when objects (such as moving insects) are present in the vicinity of the cavity. However, planar cavities suffer from significant radiative, conductive, and dielectric losses. As a result, the quality factor (Q factor) –which determines the sensitivity and resolution – of planar cavity sensors is limited to the order of 10^2 at room temperature.

Loss in the resonator can be compensated for with the integration of an active component whose amplifying features can restore lost energy (Nick, 2011). This produces a transmission spectrum with a much narrower transmission peak. Such active cavities or resonators exhibit drastically improved sensitivity and resolution as well as a resistance to lossy environments (where energy is dissipated by surrounding materials). Quality factors on the order of 10^4 are regularly achieved. The addition of an active component to improve the quality factor has been implemented in communication systems (Nick, Member, & Mortazawi, 2010), to study semiconductors (Jones, Kelly, Severtsen, & McCloy, 2013), and to sense liquids without contact (Zarifi & Daneshmand, 2015).

In this report, we propose a novel microwave based sensor for the monitoring of stored product pest insects. The sensing element of the device is a planar active microwave cavity constructed from microstrip with a Q factor as high as 21,600 even in lossy environments, which is a factor 900 greater than the conventional passive resonator (Q = 24) in the same environment. Our experimental objectives are to test: the sensitivity of the device to the movement of single insects; the dependence of the device response on insect activity; and the response of the device to the movement of insects in grain. In this study, we aimed to demonstrate the potential of the developed device as a means of rapidly detecting insects inside grain samples.

2. Materials and methods

2.1. *Experimental objectives and overview*

The goal of our experiments is to demonstrate the potential of active resonator technology as an insect detector in stored grain. Our goal was divided into three objectives. First, we sought to demonstrate that insect movement indeed produced a response in the active resonator when it came into contact with it. Second, we aimed to show that the resonator response was related to insect activity. Third, we sought, as a proof-of-concept, to demonstrate non-contact detection of insects in a grain sample.

To achieve our first objective, we placed individual adult insects in a closed area in contact with the device. We then recorded the resonator response for 10 min for indications of insect activity. The measurement was conducted at room temperature. This experiment, and all following experiments, were performed with adult *Tribolium castaneum* and *Cryptolestes ferrugineus* as test subjects.

We achieved our second objective by adjusting the temperature of the enclosed area and repeating the first experiment. We repeated the measurements at 10 temperatures between 10° and 50°. To obtain a statistical result, the measurement was replicated with 5 individuals from each insect species tested. We then combined the results to produce a plot of measured activity vs. temperature for each species.

A proof-of-concept for insect detection in grain was realised by filling the enclosed area with wheat grain, placing a single adult insect on the surface of the grain, and recording the resonator response for 10 min. We compared the response when an insect was present to when there were none. We repeated the measurement for grain depths ranging from 0.3 cm to 2.1 cm. The measurements were conducted at room temperature. We also compared the effect of the added dielectric loss of grain on passive resonators to that on active resonators.

2.2. *Experimental apparatus*

In order to test the resonator as a sensor, we constructed a device which integrates the resonator with the ability to confine insects, hold grain samples, and control temperature. Figure 1 illustrates the set-up for the experiments reported in this work. To prevent insects from escaping, a containment area was constructed on top of the resonator by fastening a 26 mm diameter, 80 mm high glass cylinder to the surface. The cylinder was closed at one end, and its open end was fixed to the resonator. To control the temperature, a Peltier cell was placed on the side of the board opposite to the resonator. The cell was supplied with a bench top power supply, and transferred heat to and from a metal optics table, which acted as a

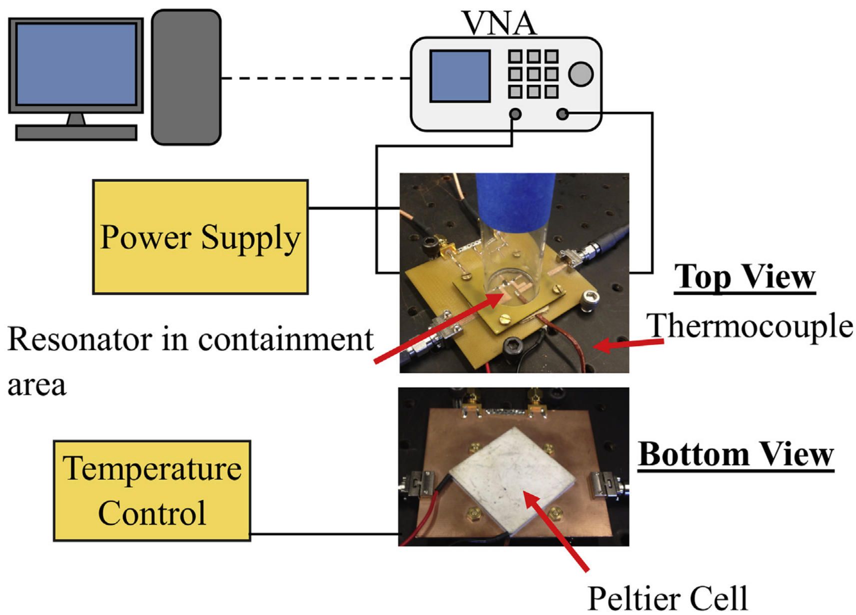

Fig. 1 – A diagram of the experimental set-up. A vector network analyser (VNA) was used to measure the transmission spectrum of the active resonator. The active resonator received external power and had a glass cylinder affixed to contain insects. On the underside of the resonator, a Peltier cell enabled heating and cooling of the resonator to control insect activity levels. The device was secured to a metal optics table top which functions as a heat sink for the Peltier cell.

thermal reservoir and on which the board was secured. The temperature of the containment area was measured using a K-type thermocouple with a Fluke 179 digital multimeter (Everett, WA, USA).

The resonators were fabricated using microstrip technology. The planar cavities were designed using Computer Simulation Technology (CST) Studio (Darmstadt, Germany) and constructed in-house by milling a double-sided 35 μm copper clad FR-4 substrate for the active resonator and Rogers DiClad 527 substrate[1] (Rogers, CT, USA) (which has lower dielectric loss than FR-4) (Rogers Corporation, 2017) for the passive resonator using a LPKF ProtoMat S103 board milling machine (Garbsen, Germany). The thickness of both substrates was 1.6 mm. Each resonator was gap-coupled in series to 50 Ω transmission line. An Agilent PNA-L N5230C vector network analyser (VNA) (Santa Rosa, CA, USA) was used to measure the frequency response of the resonators. Here, the transmission coefficient was measured as S_{21}, a complex vector quantity whose magnitude, $|S_{21}|$, is equal to the ratio of the device output to input voltage wave amplitudes and is commonly expressed on either linear or logarithmic (decibel) scales. Unless specified otherwise, the output power of VNA was set to −20 dBm with −20 dB external attenuation resulting in −40 dBm (0.1 μW) power input to the sensor and an IF bandwidth (the bandwidth of the baseband IF filter internal to the VNA) setting of 1.5 kHz. For all measurements, the testing area was shielded with microwave absorber [Cumings Microwave C-RAM LF-77 (Avon, MA, USA)] to block interfering signals during measurement.

[1] The designation "FR-4" refers to a grade of material defined by its mechanical, chemical, and electrical properties and is a common choice of substrate for printed circuit boards. Conversely, DiClad 527 is a specific material product offered by Rogers Corporation.

2.3. *Insects and grain*

We tested two stored-product insects; the rusty grain beetle, *C. ferrugineus* (Stephens) (Laemophloeidae: Coleoptera) and the red flour beetle, *T. castaneum* (Herbst) (Tenebrionidae: Coleoptera). The insects were collected from a grain storage in Manitoba, Canada in 2013, and reared at 30° since that time. *C. ferrugineus* was reared on Hard Red Spring wheat kernels, cracked wheat and wheat germ. *T. castaneum* was reared on white flour with 5% brewers yeast. Only adult insects having emerged from pupae less than 2 months prior were used in this study.

The grain used in the grain sample tests was Hard Red Spring wheat (cv. Carberry) with a moisture content of 12.9% ± 0.1% (ASABE, 2014).

2.4. *Procedure for contact sensing experiment*

In our first experiment, we used the sensor to detect insect activity by contact. We placed a single adult on the surface of the resonator and recorded the transmission spectrum. Insect movement on the surface caused the transmission spectrum to shift (Fig. 2). A glass cylinder (26 mm diameter, 80 mm height) was fastened to the sensor board to prevent insect escape (Fig. 1). The containment area was at a room temperature of approximately 23°. To reliably detect the insect, we continuously recorded S_{21} for about 10 min, corresponding to 960 individual spectrum measurements. From the measurement, we determined the peak transmission frequency, f_0, using a peak fitting algorithm.

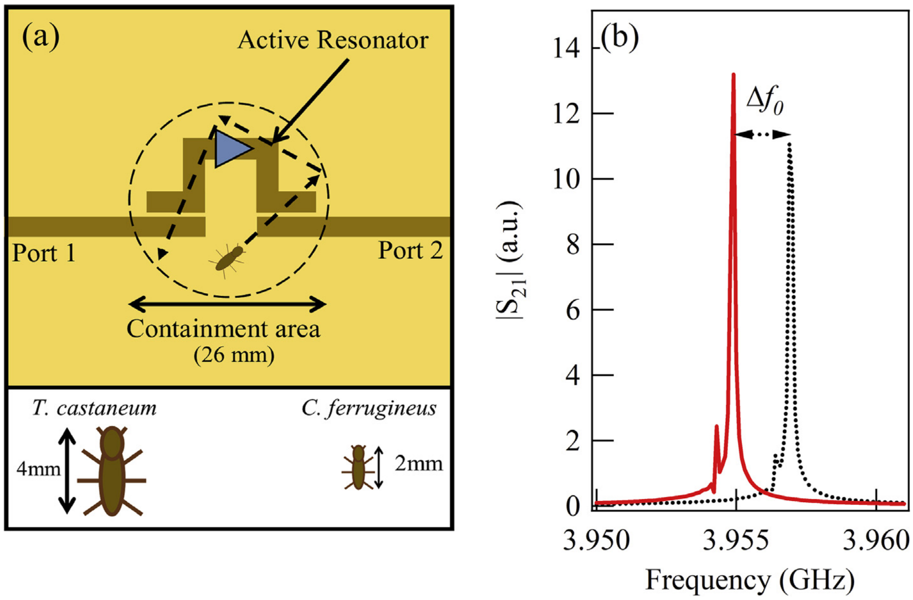

Fig. 2 – The sensor could detect insects by contact. (a) a single insect was placed on the resonator surface and is confined by a glass cylinder (26 mm diameter). The measurement was repeated with two insect species: *Tribolium castaneum* and the smaller *Cryptolestes ferrugineus*. (b) Changes in insect position caused a shift of the peak transmission frequency, f_0, of the resonator.

2.5. *Procedure for activity measurement*

An insect was placed in the containment area and allowed to move freely on the surface of the resonator, as in Section 2.4. A Peltier cell placed under the board enables heating and cooling of the resonator (Fig. 1) depending on the polarity of the voltage bias. The temperature was controlled by adjusting the voltage supplied to the Peltier cell. Insect activity was measured for 10 temperatures ranging from 10° to 50°. For each temperature point, the containment area was left to equilibrate – a process taking approximately 10 min – before data were recorded. We then recorded the transmission spectrum over a 10 min period at a constant rate of approximately one every second, corresponding to 600 individual measurements. The measurement was repeated with 5 adult individuals from each species. The measurement area was shielded from interfering radiation.

From the recorded spectra, f_0 as it varied with time was obtained. A statistical analysis of the recorded activity was performed. To quantify the level of insect activity at a given temperature, the average of the absolute difference in f_0 between consecutive time points was calculated for that measurement. This average is labelled δf_0 in this report. Then, the overall mean across all measurements and the standard error of the mean were calculated for each temperature, for both species. In this way, the level of insect activity as it varies with temperature was estimated.

2.6. *Procedure for detection in a grain sample*

An important practical application of the sensor is the detection of insects in grain samples or bulks. First, we compared the effects of the dielectric loss caused by grain when it covered a passive resonator and active resonator. This was done by gradually filling the containment area of the test device with grain until the further addition of grain did not affect the transmission spectrum of the resonator (roughly 3 cm for the active resonator). This was repeated for the passive resonator and the active resonator, and the transmission spectrum of each was recorded in the cases with and without grain.

As a proof-of-principle of detection in grain, we partially filled the 26 mm glass cylinder with wheat grain and introduced a single insect on the surface of the wheat held inside the cylinder. We then recorded the transmission spectrum every 0.6 s for 10 min. Over the course of the measurement, the insect was left free to move on and inside the wheat sample. The measurement was repeated with grain heights varying from 0.6 cm to 2.1 cm for *T. castaneum* and 0.3 cm–1.2 cm for *C. ferrugineus*. The measurements were conducted at room temperature of approximately 23° and the sensor was shielded from interfering radiation.

To quantify the measured activity, we measured δf_0 in the same way described in Section 2.5.

3. Results and discussion

3.1. *Contact sensing*

The frequency at which maximum transmission occurs, f_0, is plotted in Fig. 3 (a) and (b). A clear signal was observed for both species, and the magnitude of the shifts was found to depend on the size of the insect and its trajectory through the sensitive area of the resonator. The greatest shift was observed when the insect was located in one of the two coupling gaps,

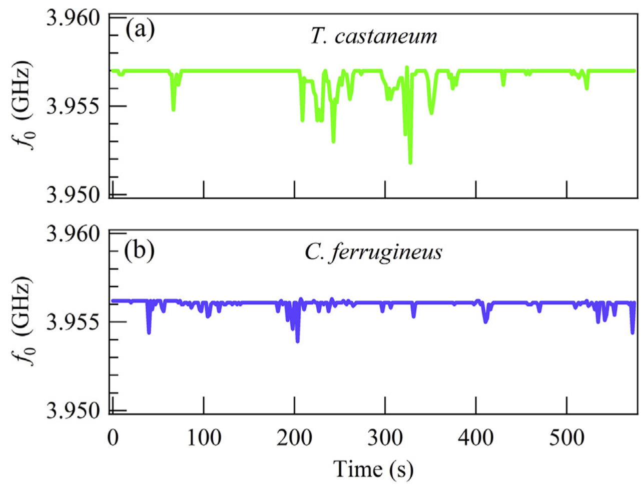

Fig. 3 – Typical measurements of the recorded peak transmission frequency, f_0, over time, for each species tested.

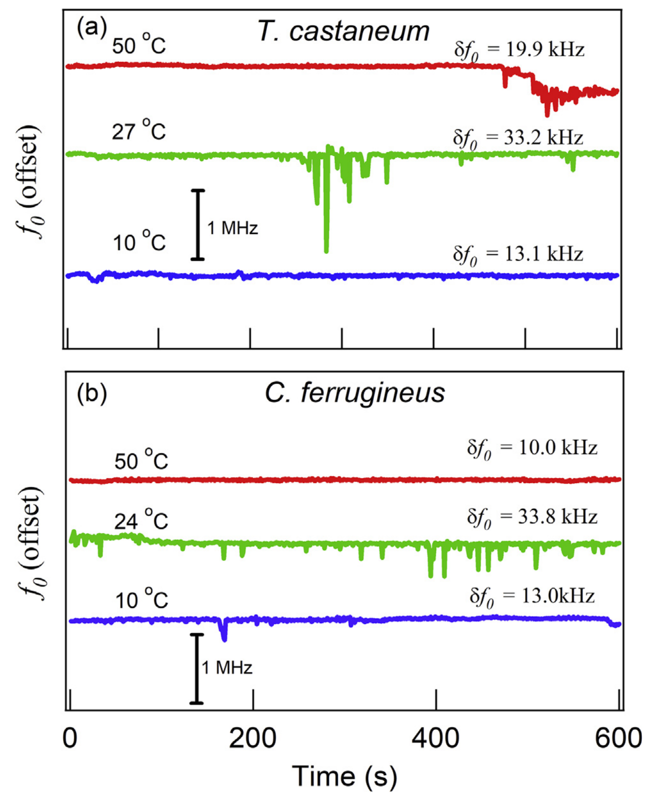

Fig. 4 – The peak transmission frequency (f_0) over 10 min measurement periods when a single insect was placed in the containment area for different temperatures. The average absolute peak shift between consecutive spectrum measurements (δf_0) was used as a measure of the activity. The spectrum was recorded approximately every second for 10 min.

because signals must transmit through these gaps to enter or exit the resonator. Unsurprisingly, the maximum shift of 5 MHz caused by the larger *T. castaneum* was greater than the 2.5 MHz shift caused by *C. ferrugineus* (half the size of *T. castaneum*). This is because *T. castaneum* occupied a greater portion of the electric field than *C. ferrugineus*, so its effect on the resonance was stronger. The fact that the resonance shifts spanned a range of values and did not simply jump between two states indicated that the transmission peak shifted gradually as the insect moved through the electric field of the resonator, whose strength was position-dependent. The maximum shifts correspond to instances when the insect was located in the region where the electric field was strongest, viz. the coupling gaps and the edges of the resonator structure. When the insect was on the edge of the containment area (where the microwave fields were weak) no shifts are apparent. For this measurement the VNA was configured for a sufficiently large bandwidth to capture the shifts but also rapid enough to capture insect movement. With these settings, insect movement at the periphery of the glass cylinder was not apparent. However, as we show in Section 3.3, it is possible to detect insect movement without direct contact to the device.

3.2. *Activity measurement*

Insect activity depends strongly on the ambient temperature. *T. castaneum* and *C. ferrugineus* movements are greatly reduced at temperatures below 10 °C (Mahroof, Subramanyam, Throne, & Menon, 2003) and 8 °C (Arlene-Christina et al., 2014), respectively. Temperatures greater than 45 °C are fatal to both species (Jian, Fields, Hargreaves, & Jayas, 2015). In our second experiment, we demonstrated the ability of the sensor to monitor insect activity by performing contact measurements at different temperatures.

Figure 4 displays the peak transmission frequency for both species at selected temperatures spanning the range of temperatures to which insects were exposed. Figure 5 shows the mean insect activity level calculated as described in Section 2.5 for all the temperatures tested.

T. castaneum is about 2 times longer than *C. ferrugineus*, and therefore causes larger shifts, which accounts for its generally greater measured activity. In both species, the measured activity was highest between 20 and 30 °C and decreased outside this range. For both species, measured activity lowered at low temperatures, which is in agreement with the published observations that temperatures below 15 and 17.5 °C inhibit movement in *T. castaneum* (Jian, Jayas, & White, 2005) and *C. ferrugineus* (Jian, Jayas, White, & Muir, 2002), respectively. On the other hand, temperatures greater than 40 °C are uncomfortable for both species and caused them to circle the edge of the containment area in an attempt to seek cooler temperatures, explaining the relative decrease in measured activity in this temperature range. Temperatures greater than 50 °C will kill most individuals from both species after 2 h exposure (Arlene-Christina et al., 2014; Mahroof et al., 2003). Conversely, *C. ferrugineus* prefers temperatures of 30–36.5 °C (Jian, Jayas, & White, 2003) and *T. castaneum* has been observed to move along a temperature gradient to areas of 30 °C (Jian et al., 2005) suggesting a preference for similar temperatures, and so activity measured in this temperature range was markedly lower. Activity was highest from 20 to 30 °C because the temperature was not so low as to inhibit movement, not too comfortable as to discourage movement, and not so high as to incite escape.

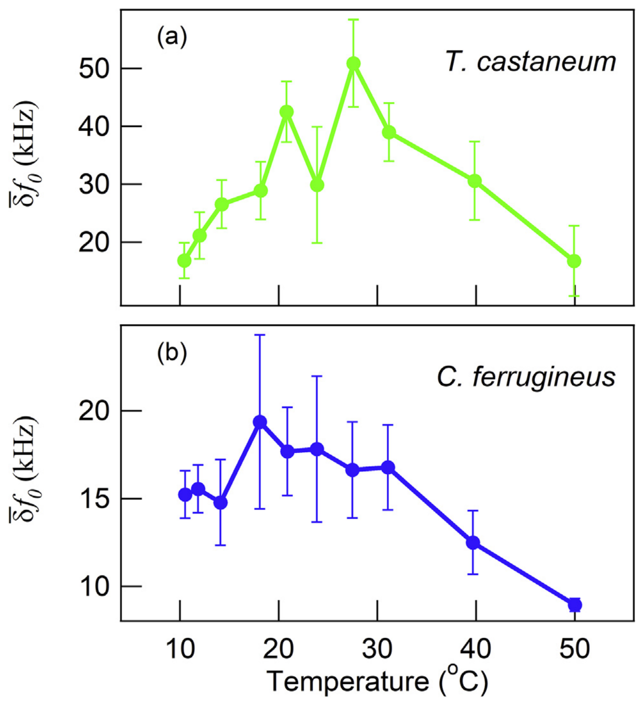

Fig. 5 – The measured activity of both species as it varied with the temperature of the containment area. The points shown are averages across 5 repetitions, each with different individuals, for each species. Verticals error bars represent the standard error of the mean.

3.3. *Detection in grain samples*

The grain increases the difficulty of insect detection through several factors: 1) insect movement is restricted to the pore spaces between kernels; 2) the contrast between the dielectric constant of the insect and the grain environment is lower compared to that with an air environment, so the response of the sensor to the insect may be weaker; 3) grain introduces dielectric loss and increases the resonance width, which decreases the sensor's ability to resolve resonance shifts. Of these factors, we expected the first and last to be most important. Peak broadening was mitigated by using an active resonator, which experiences minimal peak broadening against loss and thus could detect the movement of insects in grain samples.

As a demonstration of the effects of grain on the transmission spectrum of the resonator, we covered with wheat grain a passive resonator and compared the result to when we did the same to the active resonator. The results are shown in Fig. 6. The construction of the passive resonator is described in Section 2.2. The effect of the increased dielectric absorption was significant in the passive resonator, whose resonance width increased by over 350% [Fig. 6 (a)]. Conversely, the active resonator experienced an increase in resonance width of only roughly 20% while maintaining a very sharp transmission peak [Fig. 6 (b)]. As we show below, the resistance of the active resonator to increased dielectric loss was crucial to its ability to detect insects in grain.

Figure 7 shows the response of the sensor to single insects in grain samples of various sizes. Using the case without insects [Fig. 7 (b)] as a reference, we saw an indication of activity for *T. castaneum* in Fig. 7 (c) and *C. ferrugineus* in Fig. 7 (d), which had manifested as a signal with seemingly random variations as well as temporary deviations of noticeably greater amplitude. These features might reflect two scales of motion: the random short scale motion of the insect as it searched for paths between individual grains and the longer scale motion as it moved through the sample.

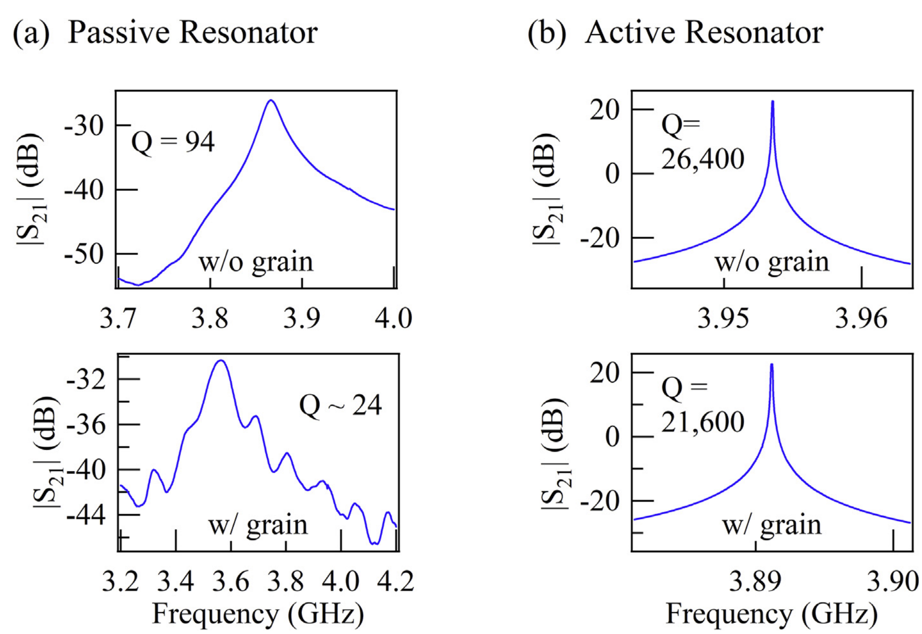

Fig. 6 – (a) the transmission spectrum, $|S_{21}|$ as a function of the microwave frequency, of an air-loaded (no grain) and grain-loaded passive resonator. (b) $|S_{21}|$ of an air-loaded and grain-loaded active resonator. Note the difference in horizontal scales between the two resonators. Loading the resonator with grain also caused a shift in the transmission peak. $|S_{21}|$ is depicted on a dB scale.

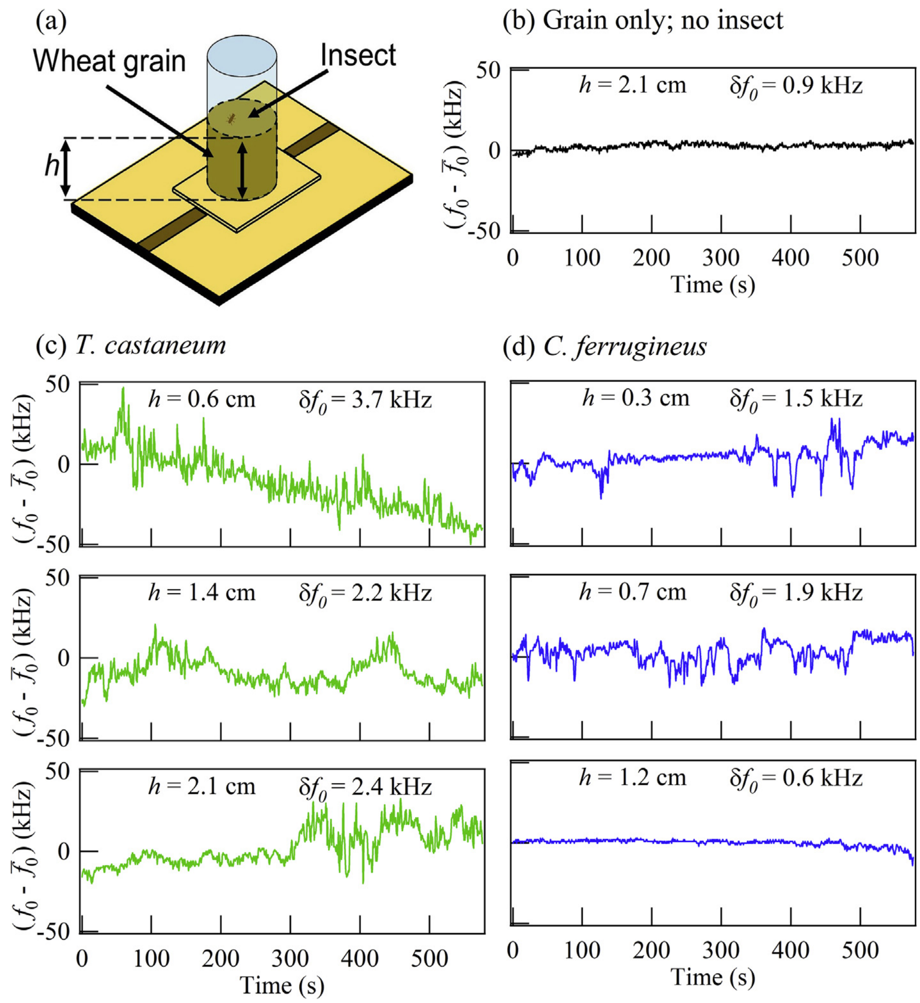

Fig. 7 – The peak transmission frequency, f_0, over time when the containment area was filled with grain of height *h*. (a) a diagram of the set-up. (b) f_0 over time when grain without insects was placed in the containment area. The values presented are adjusted by the subtracting the average of f_0 for the measurement, $\overline{f_0}$, from all points. (c) a single *T. castaneum* insect in, 0.6 cm, 1.4 cm and 2.1 cm of grain, respectively; (d) a single *C. ferrugineus* insect in 0.3 cm, 0.7 cm, and 1.2 cm of grain. The average absolute peak shift between consecutive spectrum measurements (δf_0) was used as a measure of the activity. Each measurement was performed over a 10 min duration with the transmission spectrum recorded every 0.6 s.

The results highlight the necessity of the active resonator. The shifts caused by the insect in grain were dramatically smaller when compared to those from contact, decreasing from a few megahertz to at most tens of kilohertz. The greatest variations in f_0 seen in Fig. 7 span approximately 50 kHz, corresponding to 28% of the active resonator linewidth, but only 0.03% of the passive resonator linewidth when in grain [Fig. 6 (a)]. Considering that most of the variations observed in Fig. 7 were much smaller than 50 kHz and noting the width of the resonance of the passive resonator [Fig. 6 (a)], we concluded that without the active element, a passive microstrip resonator lacked the resolution to be useful for the detection of insects in grain samples.

Due to its size, *T. castaneum* movement in the grain was restricted and a net displacement from the surface where it was introduced was difficult for it to achieve (Jian et al., 2005). This may be apparent in Fig. 7 (c) and (d), where temporary changes in f_0 were observed when the insect attempted to move deeper into the grain sample but failed to find a path leading deeper and so returned to the surface and caused f_0 to return nearly to its initial value. Figure 7 (c) and (d) also show constant smaller, more rapid variations in f_0 not observed in the clean case [Fig. 7 (b)]. As the height of the sample was increased, these variations were diminished by the generally increasing distance of the insect from the resonator.

Similar features were observed in the measurement of *C. ferrugineus* movement in the grain. Since *C. ferrugineus* is significantly smaller than *T. castaneum* and was able to move more freely through the interstices of the sample, the relatively large changes in f_0 were more frequent than those observed with *T. castaneum*. However, the smaller size also reduced overall magnitude of shifts in f_0, making it more difficult to detect *C. ferrugineus* at larger distances.

4. Conclusions

4.1. Future work

Since the sensor response changes with insect activity, it has the potential for use in monitoring insect population densities in stored grain. Such monitoring is crucial for farmers and grain handlers who depend on the information to formulate their pest management strategies. A current challenge of this application is the possible ambiguities in sensor signal that results from the dependence of the response on insect size, location, and movement speed. One way to circumvent this is the use of an array of sensors sunk into grain bulks to increase the reliability of detection. For example, if the sensors in an array are monitored using individual channels, the signals received on different channels can be correlated and their amplitudes compared to estimate the location of the insects producing the signal.

The sensor could also be used to quickly test for insects in grain samples pulled from a grain bulk. Outside of agriculture and food production, the material penetrating ability of the sensor would make it a useful tool for the detection of household pests such as termites, ants, or rodents.

4.2. Summary

We have demonstrated that the sensor based on a planar microwave active cavity was capable of detecting single adult insect activity through contact as well as in grain samples. Insect activity was detected by monitoring the transmission spectrum of the cavity, which operated in the 3–4 GHz range, whose peak transmission shifted when insects were nearby. In contrast with a passive cavity, the active cavity had a very narrow transmission spectrum peak, allowing shifts on the order of kHz to be detected. Furthermore, the active cavity was resistant to added dielectric loss in the environment such that it maintained its narrow transmission peak even when placed in grain. We used two species of common grain pests as subjects in our tests: *T. castaneum* and *C. ferrugineus*. As expected, the larger *T. castaneum* caused greater shifts in the transmission peak than the smaller *C. ferrugineus*. This resulted in a lower measured activity of *C. ferrugineus*, though this did not necessarily reflect a lower level of movement. We also successfully detected the insects in wheat grain samples at distances up to 2.1 cm with *T. castaneum* and 1.2 cm with *C. ferrugineus*. Our approach has potential use as a tool to monitor insect populations in stored grain bulks, such as grain bins, or to non-destructively detect other pests such as termites.

Acknowledgements

This work has been funded by Natural Sciences and Engineering Research Council of Canada, University Collaborative Research Program of the University of Manitoba, and The National Science Foundation of China Grant No. 11429401. We thank Kim Stadnyk and Sarah Currie for technical assistance.

REFERENCES

Abduljabar, A. A., Porch, A., & Barrow, D. A. (2014). Real-time measurements of size, speed, and dielectric property of liquid segments using a microwave microfluidic sensor. In *Microwave symposium (IMS)* (pp. 1–4). IEEE MTT-S International. IEEE.

Arlene-Christina, G. D., Jayas, D. S., Fields, P. G., Jian, F., White, N. D. G., & Alagusundaram, K. (2014). Movement of *Cryptolestes ferrugineus* out of wheat kernels and their mortalities under elevated temperatures. *Journal of Stored Products Research, 59*, 292–298.

ASABE. (2014). *Standard S352.2: Moisture measurement - unground grain and seeds*. St. Joseph, MI, USA: ASABE.

Boybay, M. S., & Ramahi, O. M. (2012). Material characterization using complementary split-ring resonators. *IEEE Transactions on instrumentation and measurement, 61*, 3039–3046.

Brabec, D., Pearson, T., Flinn, P., & Katzke, D. (2010). Detection of internal insects in wheat using a conductive roller mill and estimation of insect fragments in the resulting flour. *Journal of Stored Products Research, 46*, 180–185.

Drake, V. A., & Reynolds, D. R. (2012). *Radar entomology: Observing insect flight and migration*. CABI.

Ferrier, G. A., Romanuik, S. F., Thomson, D. J., Bridges, E., & Freeman, M. R. (2009). A microwave interferometric system for simultaneous actuation and detection of single biological cells. *Lab on a Chip, 9*, 3406–3412.

Gutiérrez, A., Ruiz, V., Moltó, E., Tapia, G., & Téllez, M. (2010). Development of a bioacoustic sensor for the early detection of red palm weevil (*Rhynchophorus ferrugineus* olivier). *Crop Protection, 29*, 671–676.

Hagstrum, D., Phillips, T., & Cuperus, G. (2012). *Stored product protection*. Manhattan, Kansas, USA: Kansas State Research and Extension.

Hagstrum, D., & Subramanyam, B. (2006). *Fundamentals of stored-product entomology*. St. Paul, Minnesota, USA: AACC International.

Jian, F., Doak, S., Jayas, D. S., Fields, P. G., & White, N. D. G. (2016). Comparison of insect detection efficiency by different detection methods. *Journal of Stored Products Research, 69*, 138–142.

Jian, F., Fields, P. G., Hargreaves, K., & Jayas, D. S. (2015). Chill-coma and minimum movement temperatures of stored-product beetles in stored wheat. *Journal of Economic Entomology, 108*, 2471–2478.

Jian, F., Jayas, D. S., & White, N. D. G. (2003). Movement of adult rusty grain beetles, *Cryptolestes ferrugineus* (Coleoptera: Cucujidae), in wheat in response to 5°C/m temperature gradients at cool temperatures. *Journal of Stored Products Research, 39*, 87–101.

Jian, F., Jayas, D. S., & White, N. D. G. (2005). Movement of *Tribolium castaneum* (Coleoptera: Tenebrionidae) adults in response to temperature gradients in vertical and horizontal wheat and corn columns. *Journal of Economic Entomology, 98*, 1413–1419.

Jian, F., Jayas, D., & White, N. D. G. (2014a). How many kilograms of grain per sample unit is big enough? part I - comparison of insect detection and density estimation between manual probe sampling and Insector® system. *Journal of Stored Products Research, 56*, 60–66.

Jian, F., Jayas, D. S., White, N. D. G., Fields, P. G., & Howe, N. (2014b). An evaluation of insect expulsion from wheat samples by microwave treatment for disinfestation. *Biosystems Engineering, 130*, 1–12.

Jian, F., Jayas, D. S., White, N. D. G., & Muir, W. E. (2002). Temperature and geotaxis preference by *Cryptolestes ferrugineus* (Coleoptera: Laemophloeidae) adults in response to

5°C/m temperature gradients at optimum and hot temperatures in stored wheat and their mortality at high temperature. *Environmental Entomology, 31*, 816–826.

Jones, A. M., Kelly, J. F., Severtsen, R. H., & McCloy, J. S. (2013). Regenerative feedback resonant circuit to detect transient changes in electromagnetic properties of semi-insulating materials. *Review of Scientific Instruments, 84*, 084703.

Karunakaran, C., Jayas, D., & White, N. (2003). Soft x–ray inspection of wheat kernels infested by *Sitophilus oryzae*. *Transactions of the ASAE, 46*, 739.

Mahroof, R., Subramanyam, B., Throne, J. E., & Menon, A. (2003). Time-mortality relationships for *Tribolium castaneum* (Coleoptera: Tenebrionidae) life stages exposed to elevated temperatures. *Journal of Economic Entomology, 96*, 1345–1351.

Mankin, R. W. (2004). Microwave radar detection of stored-product insects. *Journal of Economic Entomology, 97*, 1168–1173.

Nick, M. (2011). *New Q-enhanced planar resonators for low phase-noise radio frequency oscillators*. Ph.D. thesis. Ann Arbor, MI, USA: University of Michigan.

Nick, M., Member, S., & Mortazawi, A. (2010). Low phase-noise planar oscillators based on low-noise active resonators. *IEEE Transactions on Microwave Theory and Techniques, 58*, 1133–1139.

Pearson, T., & Brabec, D. L. (2007). Detection of wheat kernels with hidden insect infestations with an electrically conductive roller mill. *Applied Engineering in Agriculture, 23*, 639–646.

Rogers Corporation. (2017). *Data sheet for DiClad series laminates*.

Singh, C. B., Jayas, D. S., Paliwal, J., & White, N. D. G. (2009). Detection of insect-damaged wheat kernels using near-infrared hyperspectral imaging. *Journal of Stored Products Research, 45*, 151–158.

Termatrac. (2017). *Termatrac website*. https://www.termatrac.com.

Yang, Y., Zhang, H., Zhu, J., Wang, G., Tzeng, T.-r., & Xuan, X. (2010). Distinguishing the viability of a single yeast cell with an ultra-sensitive radio frequency sensor. *Lab on a Chip, 10*, 553–555.

Zarifi, M. H., & Daneshmand, M. (2015). Non-contact liquid sensing using high resolution microwave microstrip resonator. In *Microwave symposium (IMS), 2015 IEEE MTT-S international* (pp. 1–4). IEEE.